

LA-UR-12-24366

Approved for public release; distribution is unlimited.

Title: Introduction to Muon Imaging

Author(s): Borozdin, Konstantin N.  
Morris, Christopher  
Perry, John O.  
Bacon, Jeffrey D.  
Schwellenbach, David D.

Intended for: Muon Meeting and JOWOG 29, 2012-09-05/2012-09-07 (Los Alamos, New Mexico, United States)



Disclaimer:

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

# Introduction to Muon Imaging

Konstantin Borozdin

Chris Morris

John Perry

Jeff Bacon

In collaboration with  
Dave Schwellenbach and NSTec

# Muon Imaging as Inspection Method

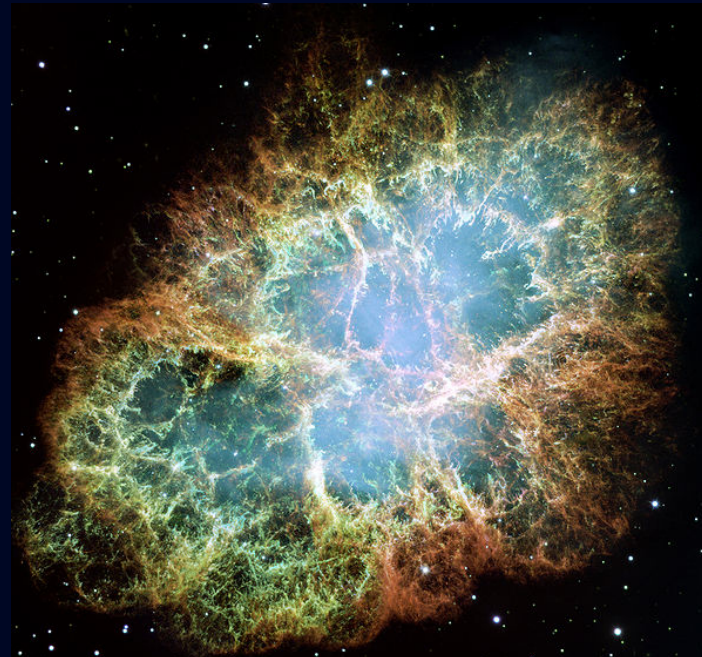
- Passive method: safe for humans and does not apply an artificial radiological dose to the warhead.
- Muon imaging is intrinsically sensitive to special nuclear materials
- Cosmic rays are much more penetrating than gamma or x-rays. SNM can be imaged behind significant shielding and inside containers.
- Exposure times depend on the object, detector configuration and imaging requirements.
- Muon imaging can be naturally adapted to information barrier concept.
- The detectors are scalable and portable, and have been demonstrated to operate for several month with little or no human intervention. The drift tubes of the detectors are sealed and do not need gas replenishment. Gas is not flammable. Detection and localization of SNM is achieved with automatic reconstruction algorithms, which can be run at a standard PC computer.
- Our detectors are also sensitive to gamma-ray and neutron radiation providing additional SNM signatures.

# Cosmic Rays: Where Do They Come From?



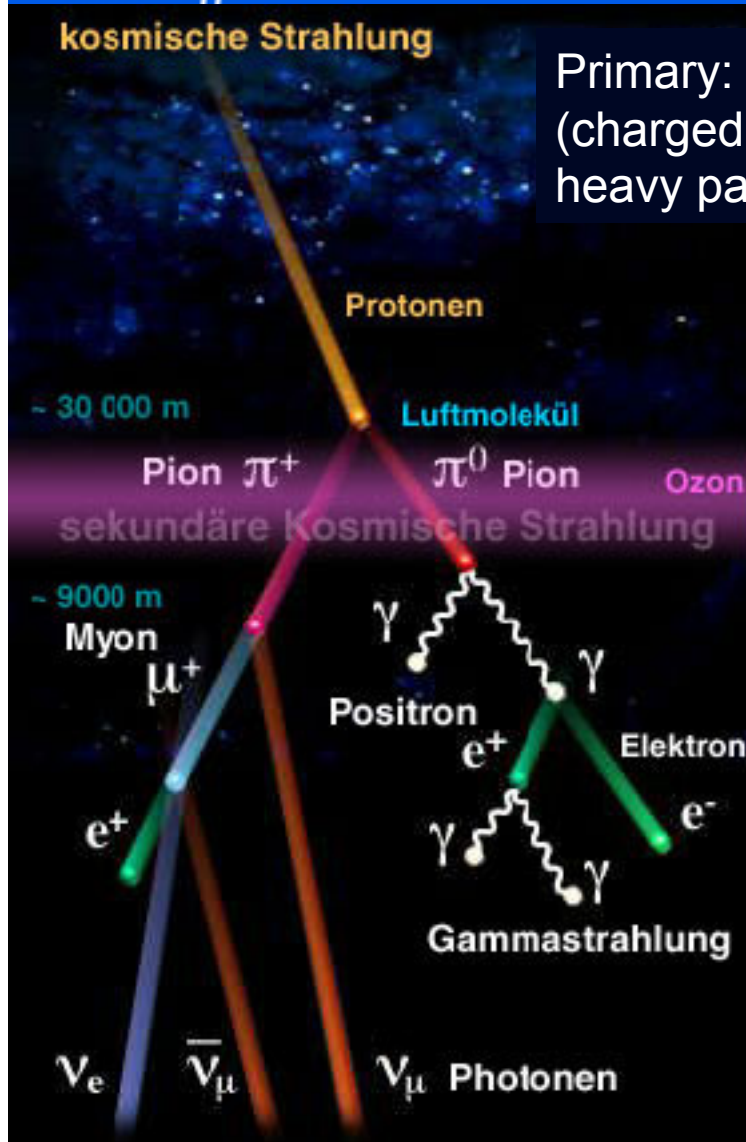
Victor Hess (1883 – 1964)  
Nobel Prize in Physics 1936

- Discovered by Victor Hess in 1912
- Consist of mainly protons, electrons, and ions
- Ray acceleration can occur in strong magnetic fields from supernova blast wave remnants
- Energies range from MeV to beyond TeV



Crab Nebula (SNR 1054 remnant)

# Cosmic Rays Conversion In Atmosphere



Primary: Mostly **protons**  
(charged, strongly interacting  
heavy particles, ~99%)

Secondary:  
Mostly **muons**  
(charged, EM-  
interacting heavy  
particles, ~70%) and  
electrons (charged,  
EM-interacting, light  
particles, ~30%).  
Neutrinos are weakly  
interacting and can be  
ignored.

Rate at sea level:

~1 per minute through  
your fingernail



~1 per second through  
your open hand

~ 10,000 per sq. meter  
per minute

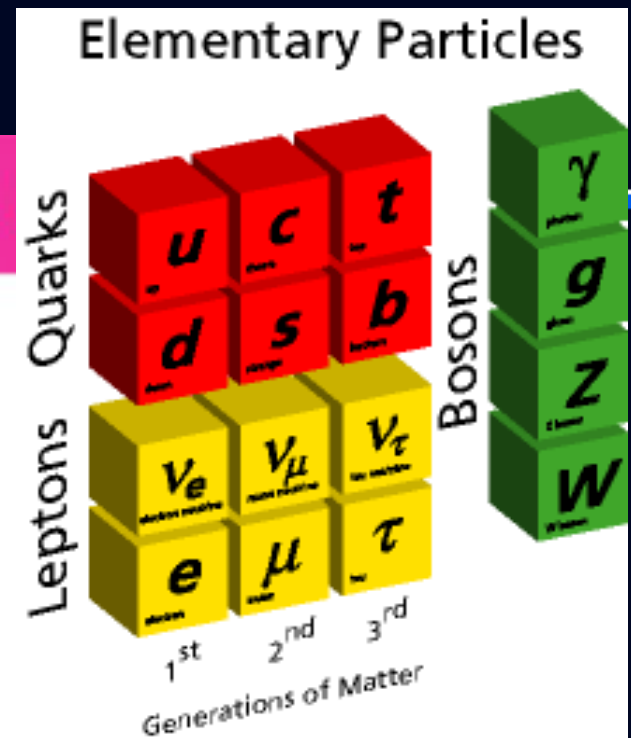
# What is Muon?

## MUON

$\mu$



The **MUON** is a short-lived, heavier version of the electron. It has the same negative charge, but is 200 times more massive than the electron.



●●●●●●●●○○○○○○○ LIGHT HEAVY

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK  
NEUTRON DOWN QUARK TAU GLUON **MUON** NEUTRINO  
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK  
UP QUARK DOWN QUARK ELECTRON NEUTRINO  
DOWN QUARK UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON  
UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON

The **PARTICLE ZOO**

$\tau$

Tauon

Mass	1,780 MeV/c <sup>2</sup>
Charge	-1 e
Lepton Number	1
Baryon Number	0
Matter/Antimatter	M

$\mu$

Muon

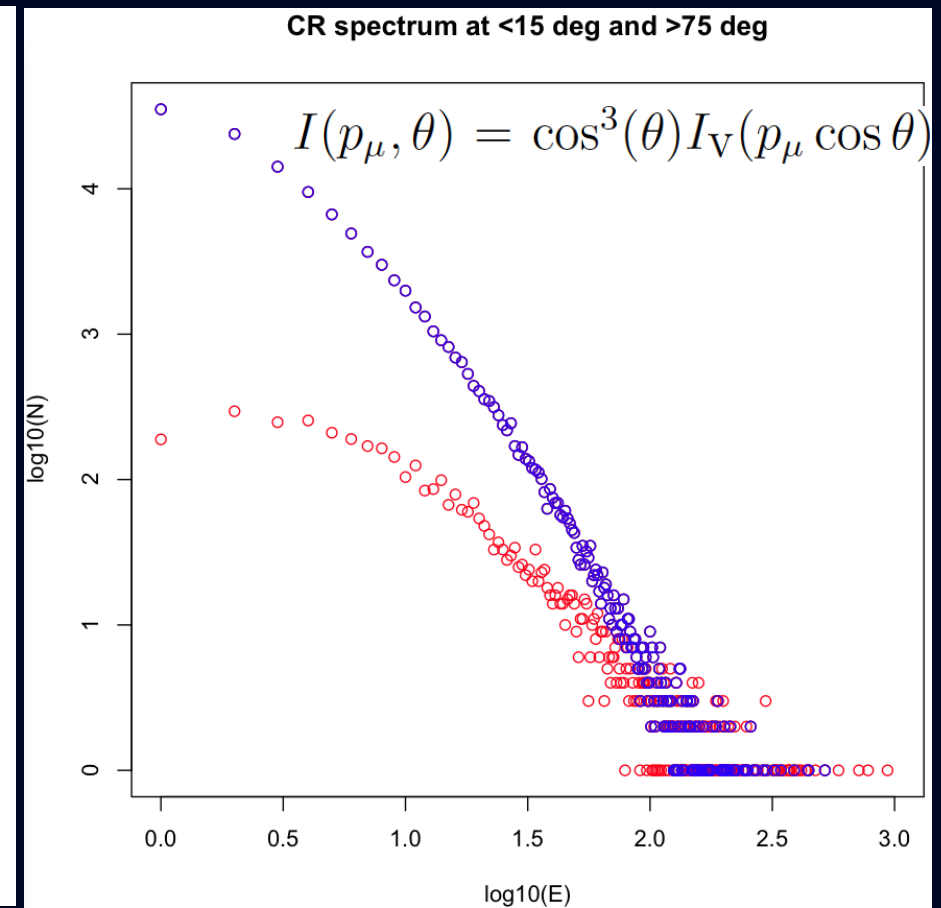
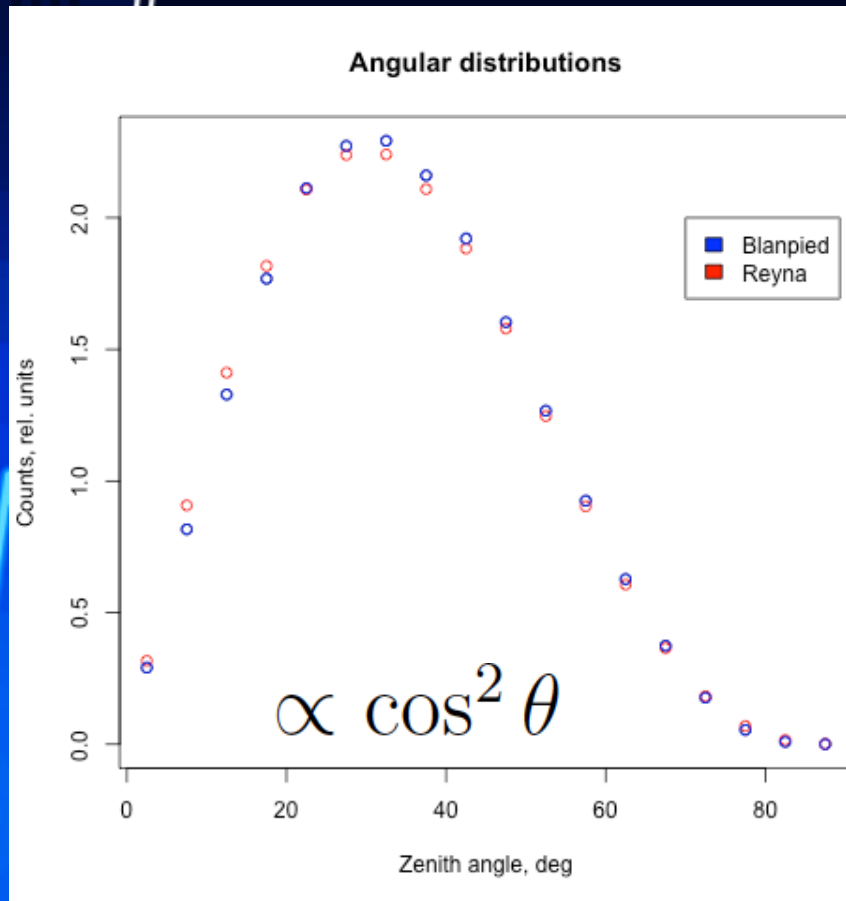
Mass	106 MeV/c <sup>2</sup>
Charge	-1 e
Lepton Number	1
Baryon Number	0
Matter/Antimatter	M

$e$

Electron

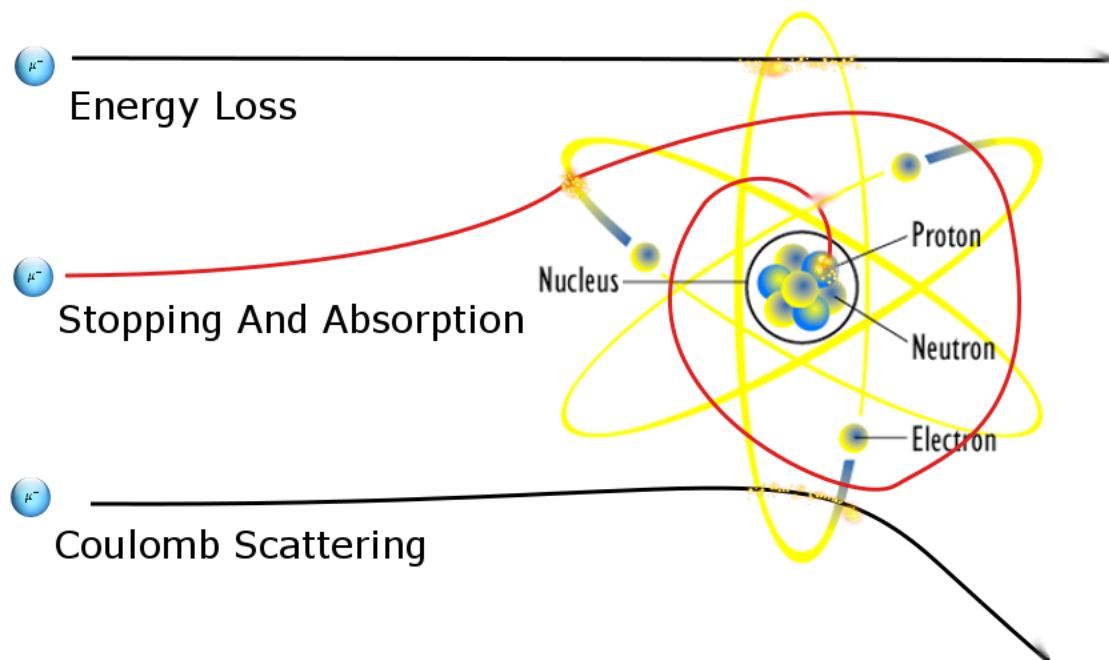
Mass	0.511 MeV/c <sup>2</sup>
Charge	-1 e
Lepton Number	1
Baryon Number	0
Matter/Antimatter	M

# Muon Flux and Spectrum as a Function of Zenith Angle



# Muon Interactions In Materials

- Energy loss
- Multiple scattering
- Stopping and absorption



# Cosmic-Ray Muons Penetrate Large Objects

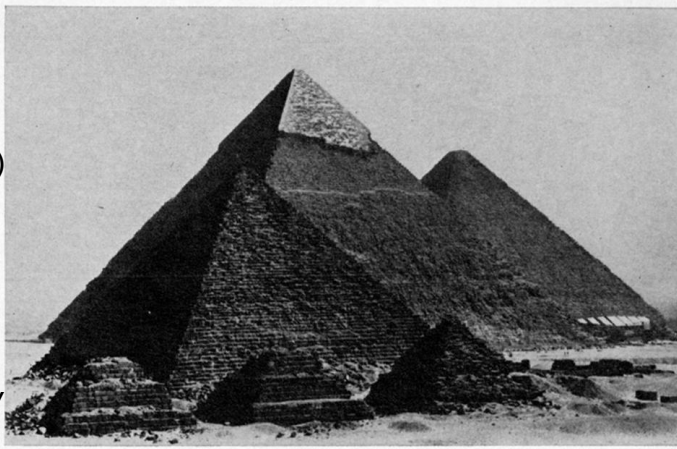
## Searching for Hidden Chambers in Pyramids

Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]

Luis Alvarez, et. al.  
*Science* **167**, 832 (1970)

Arturo Menchaca, et. al.  
see

[http://  
www.msnbc.msn.com/  
id/4540266/](http://www.msnbc.msn.com/id/4540266/)



## Predicting Volcanic Eruptions

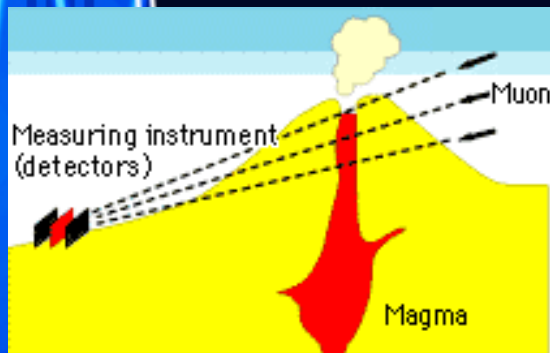


Figure 4: Analyzing the internal structure of a volcanic zone using muons

Tanaka, Nagamine, et. al.  
*Nuclear Instruments and Methods A* **507**:3, 657 (2003)

Muon transmission  
radiography –  
Well established  
since the mid 1900s

## Measuring Tunnel Overburden

Commonwealth Engineer, July 1, 1955

E.P. George 1955

455

### Cosmic Rays Measure Overburden of Tunnel

• Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehone and Mr. O'Neill.



Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

By Dr. E. P. George  
University of Sydney, N.S.W.

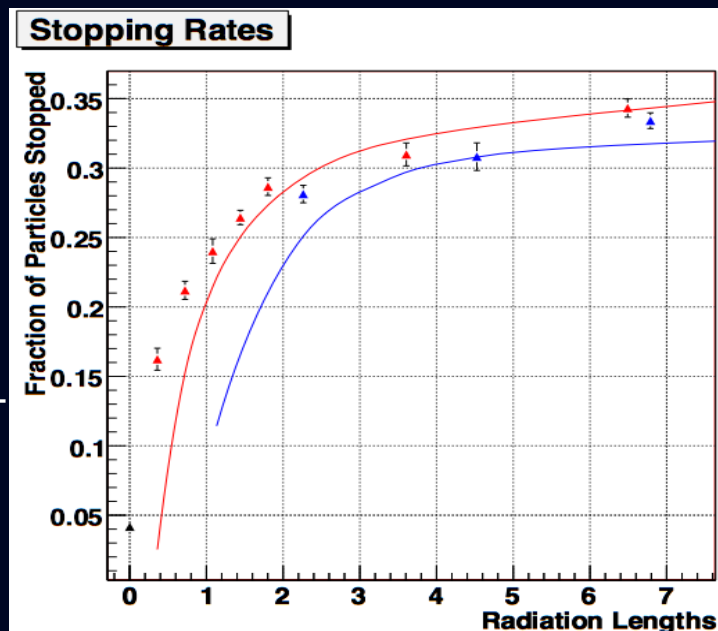
Los Alamos  
NATIONAL LABORATORY

EST 1943

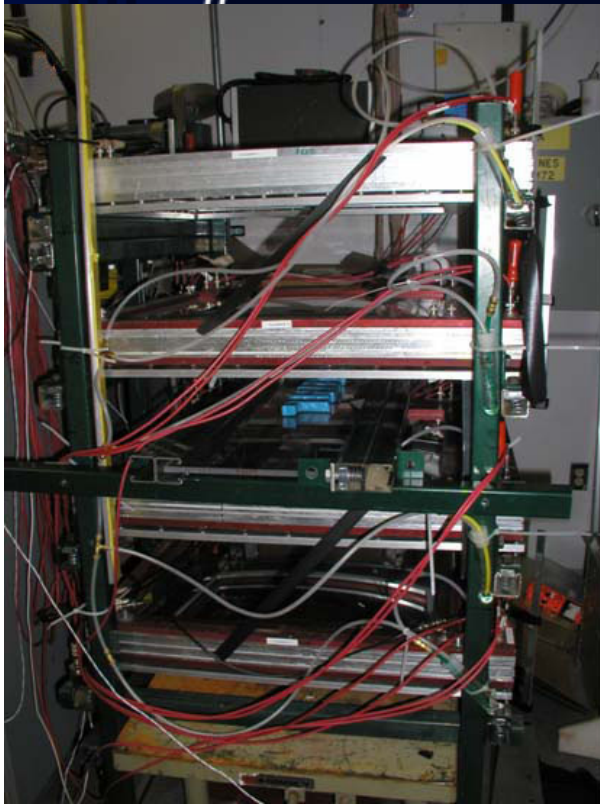
# Attenuation of Cosmic Rays in Small Objects

- Attenuation approach doesn't work for particles that are all pass (neutrinos) or all stopped (optical photons)
- Optimal attenuation fraction is  $\sim 0.5$
- Because cosmic rays has both hard (muons) and soft (electrons) components, we can combine these signals together to get a reasonable attenuation fraction for smaller objects

The solid lines in the figure are from the Monte-Carlo (GEANT) model. Due to different energy loss mechanisms the iron (red) and lead (blue) data (both measured and simulated) do not lie on top of each other. The saturation of curves at stopping rates of 30-35% indicates that most of the soft component electrons are stopped.



# Attenuation in Small Objects



Iron

Aluminum

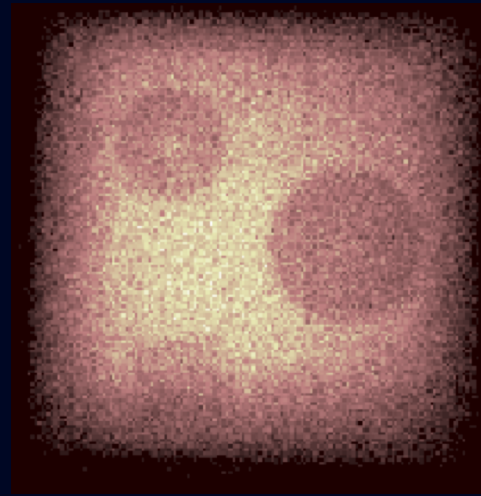


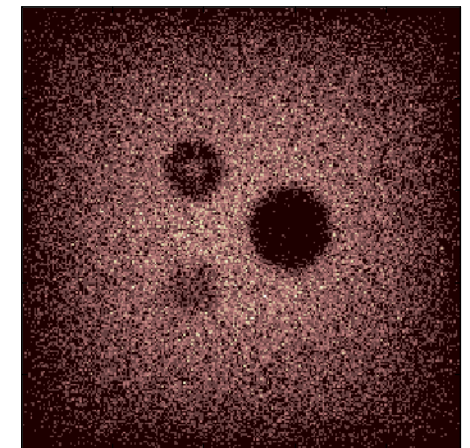
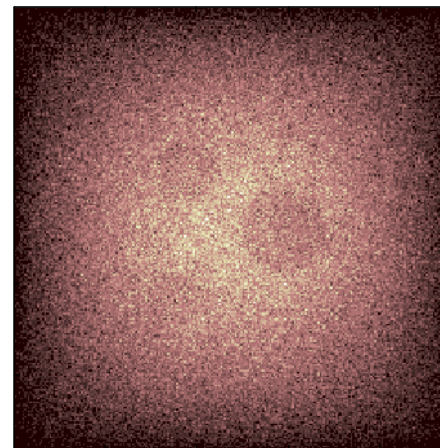
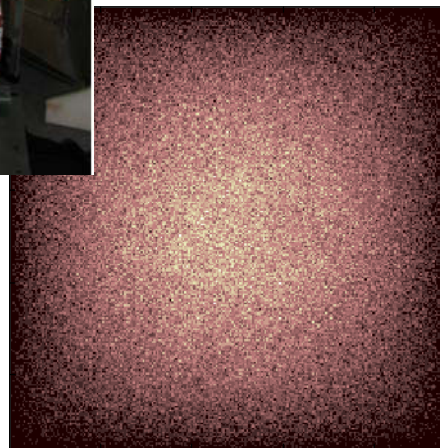
Image of muon  
“shadows” created by  
three objects.

Tungsten

Simulation,

Simulation, and e

Simulation, e



# Muon Imaging Start at Los Alamos



9/11 terrorist attack

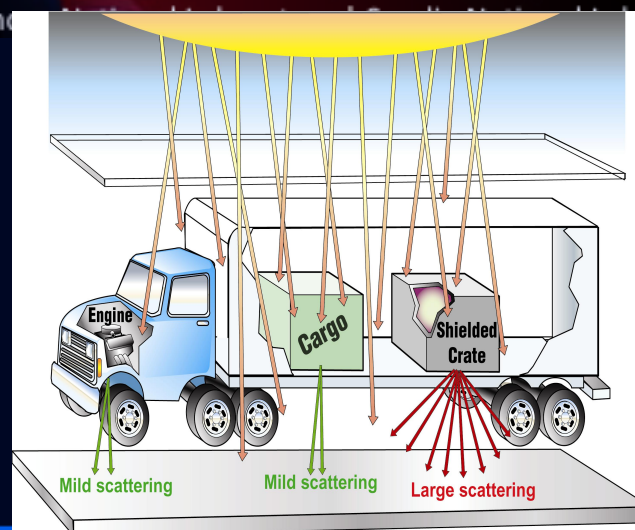
LDRD special call

## LDRD

Laboratory Directed Research & Development

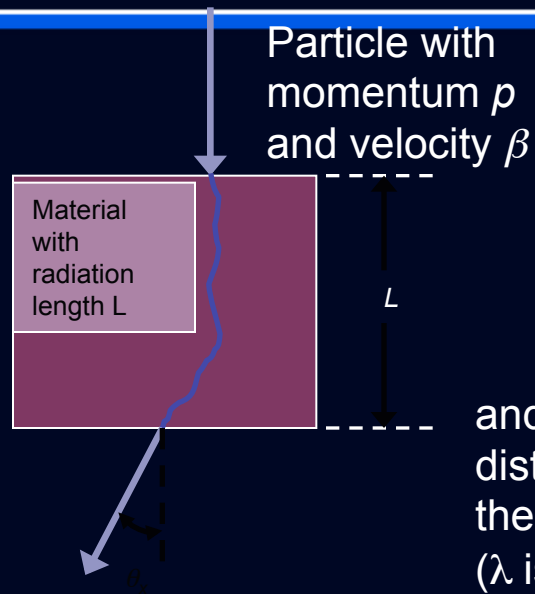
Los Alamos National Laboratory | Lawrence Livermore National Laboratory

Muon Radiography concept



# Another Signature: Multiple Scattering

multiple scattering signal is large for high-Z, high-density objects



Scattering distribution is approximately Gaussian

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

and the width of the distribution is related to the material  
( $\lambda$  is a radiation length)

$$\theta_0 = \frac{13.6}{p\beta} \sqrt{\frac{L}{\lambda}}$$

Scattered particles carry information from which material may be identified.

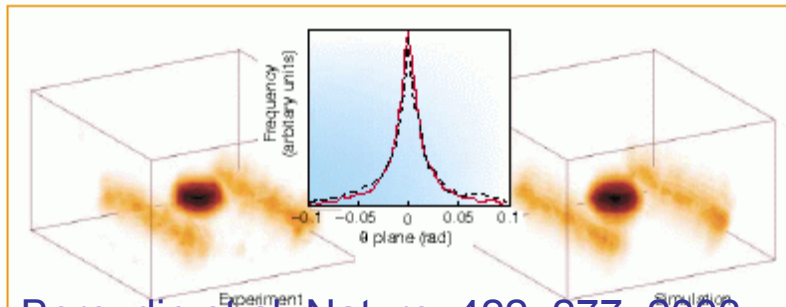
Material	$\lambda$ , cm	$\theta_0$ , mrad*
Water	36	2.3
Iron	1.76	11.1
Lead	.56	20.1
*10 cm of material, 3 Gev muons		

# Muon Scattering Can Be Used to Find SNM

## Radiographic imaging with cosmic-ray muons

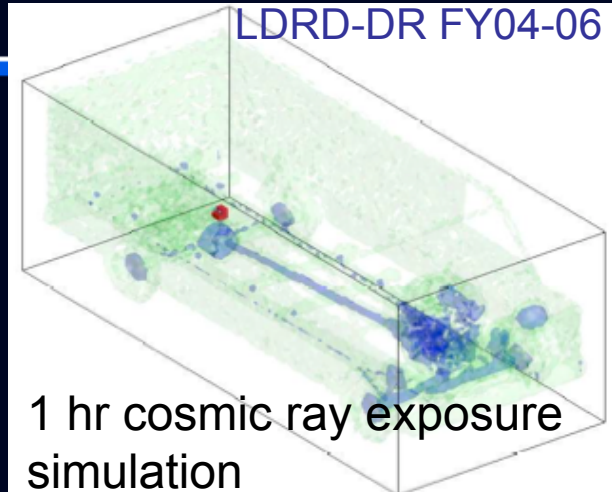
Natural background particles could be exploited to detect concealed nuclear materials.

Despite its enormous success, X-ray radiography<sup>1</sup> has its limitations: an inability to penetrate dense objects, the need for multiple projections to resolve three-dimensional structure, and health risks from radiation. Here we show that natural background muons, which are generated by cosmic rays and are highly penetrating, can be used for radiographic imaging of medium-to-large, dense objects, without these limitations and with a reasonably short exposure time. This inexpensive and harmless technique may offer a



Borozdin et al. Nature, 422, 277, 2003

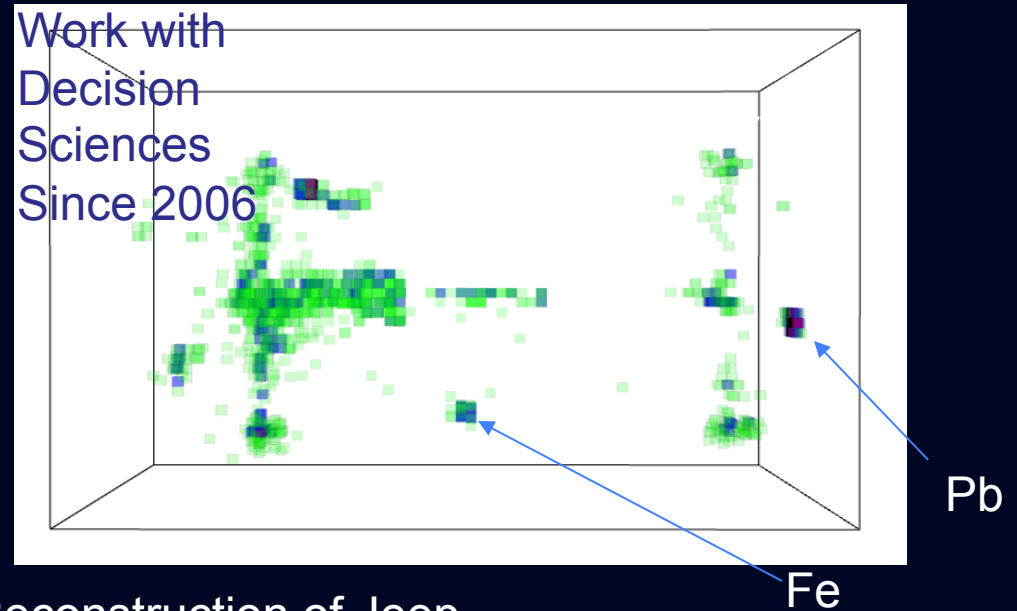
LDRD-DR FY04-06



1 hr cosmic ray exposure simulation



Work with  
Decision  
Sciences  
Since 2006



Reconstruction of Jeep  
with 3 objects

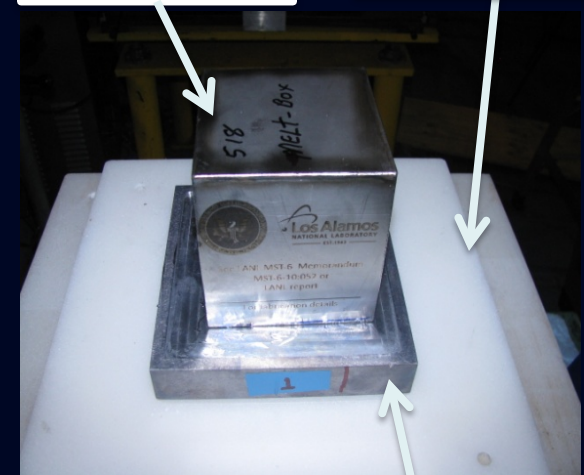
# Detecting SNM Inside the Shielding

Shielding + U

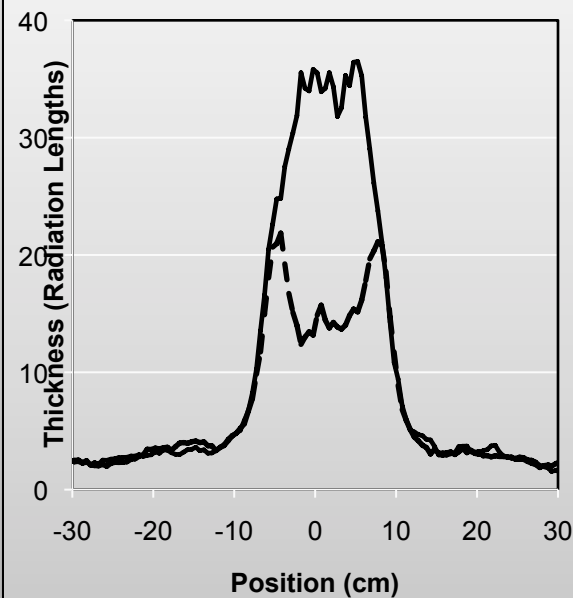
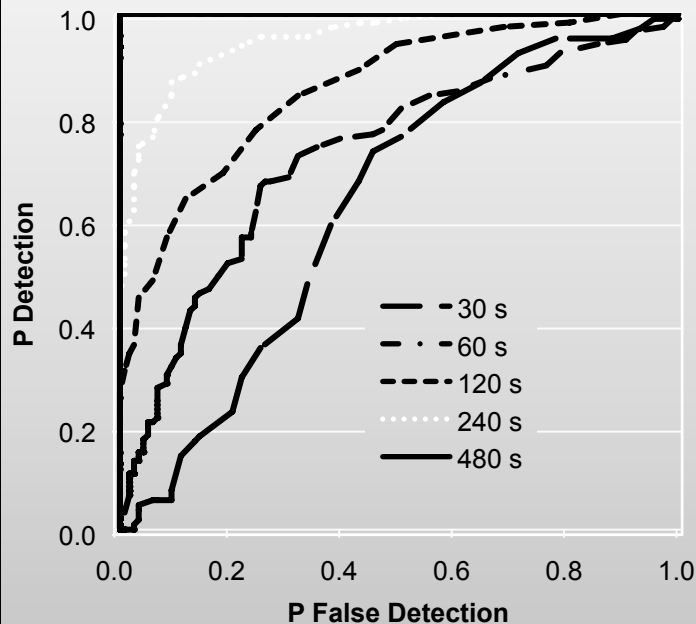
Shielding only

20 kg LEU

15 cm HDP



2.5 cm Pb

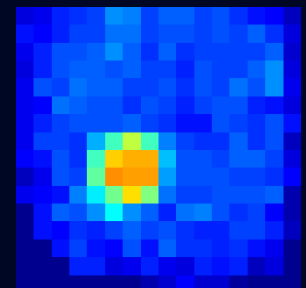
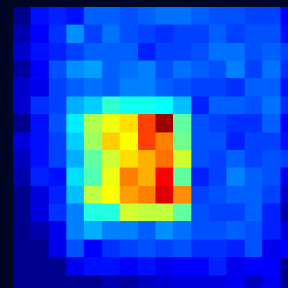
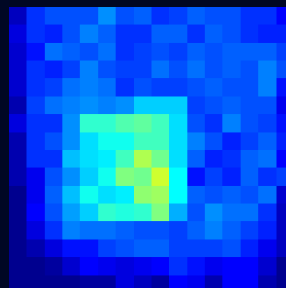
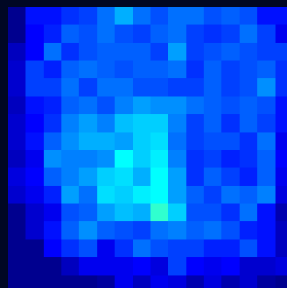
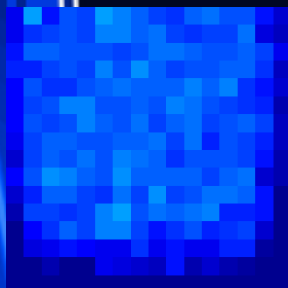
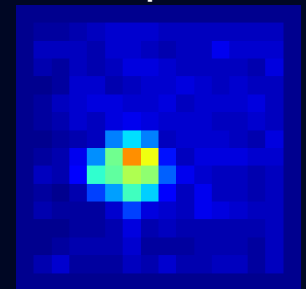
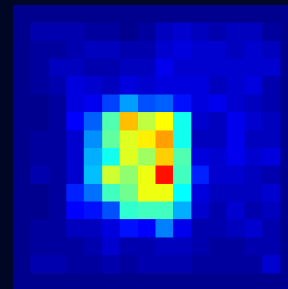
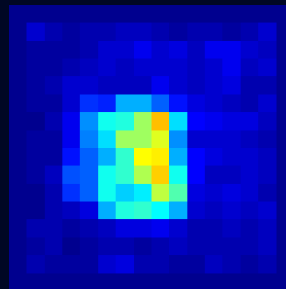
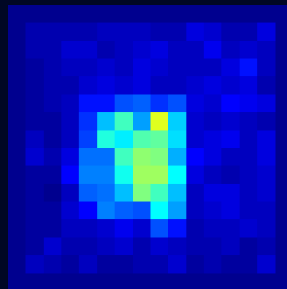
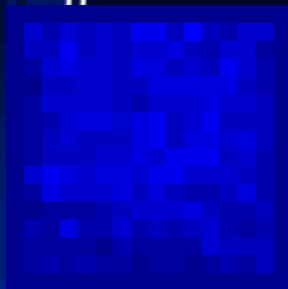


# Transmission and Scattering Can Be Combined

empty

Step wedges: Al, Pb and W

Lead  
hemisphere

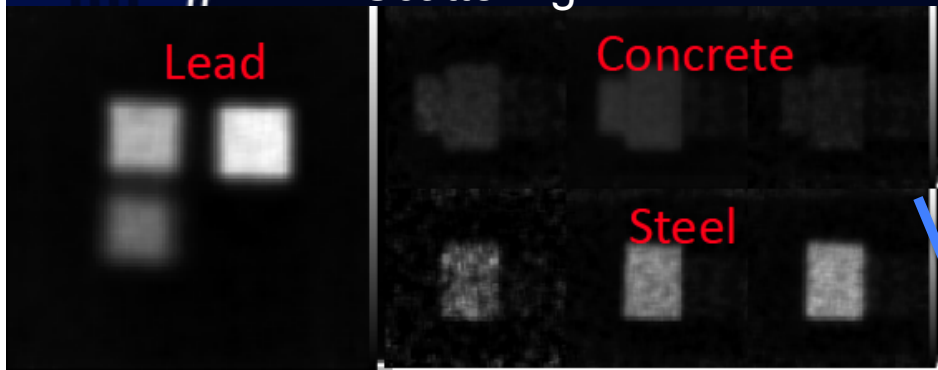


Stopping: upper row (0-200 rel. units)

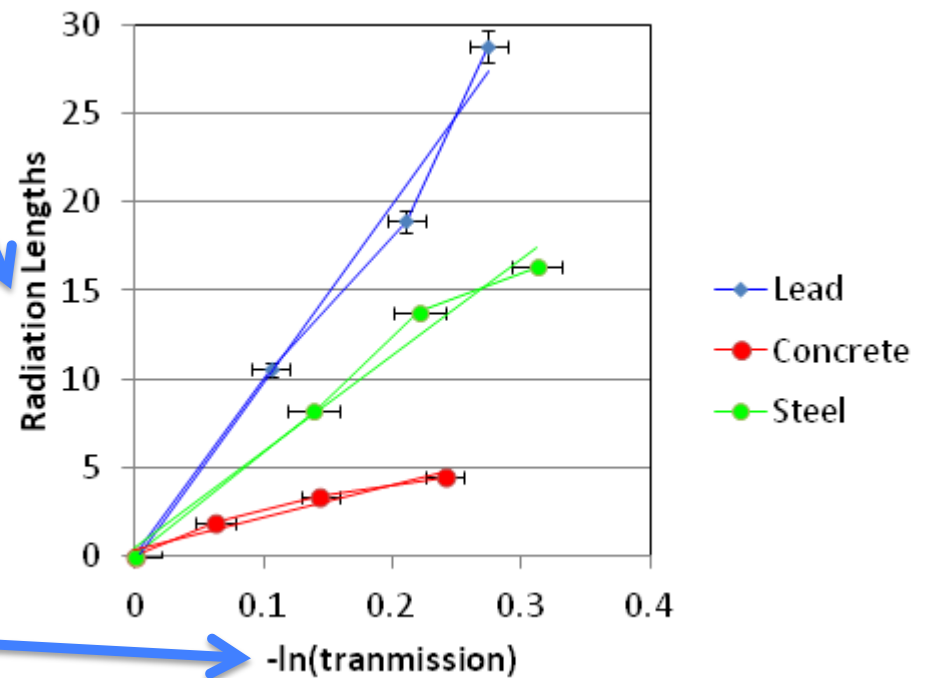
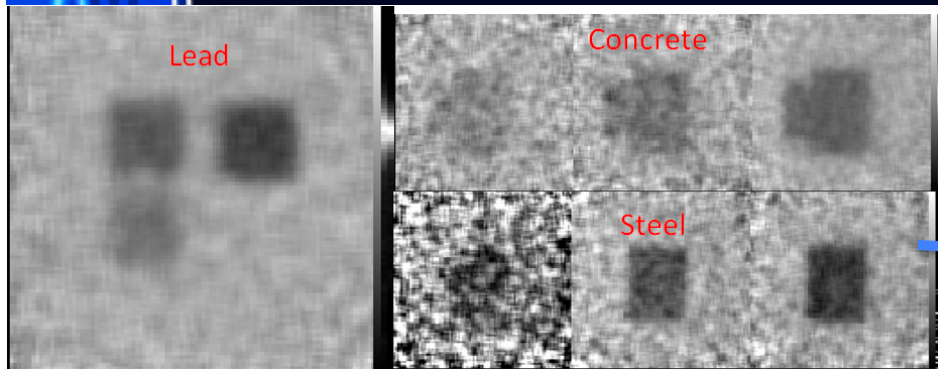
Scattering: lower row (0-50 rel. units)

# Two Sources of Information Provide Material ID

Scattering

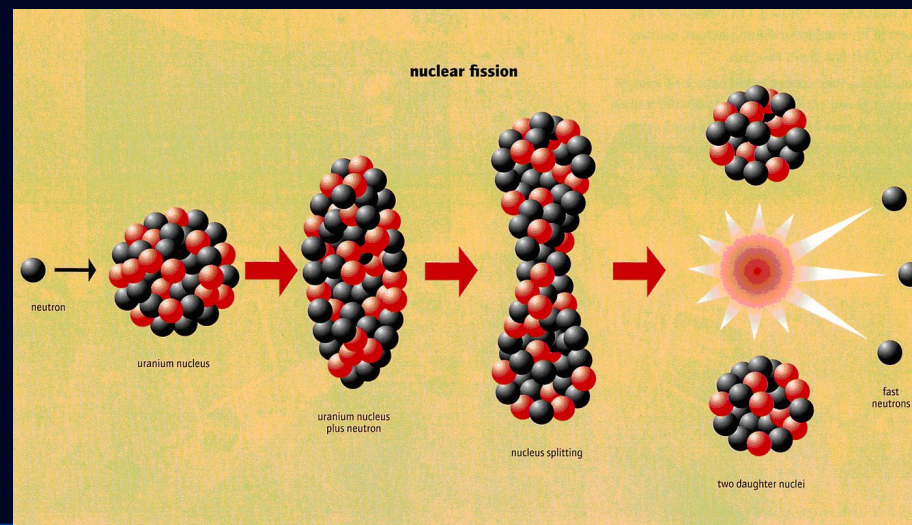


Transmission



# What Muons Do When They Stop

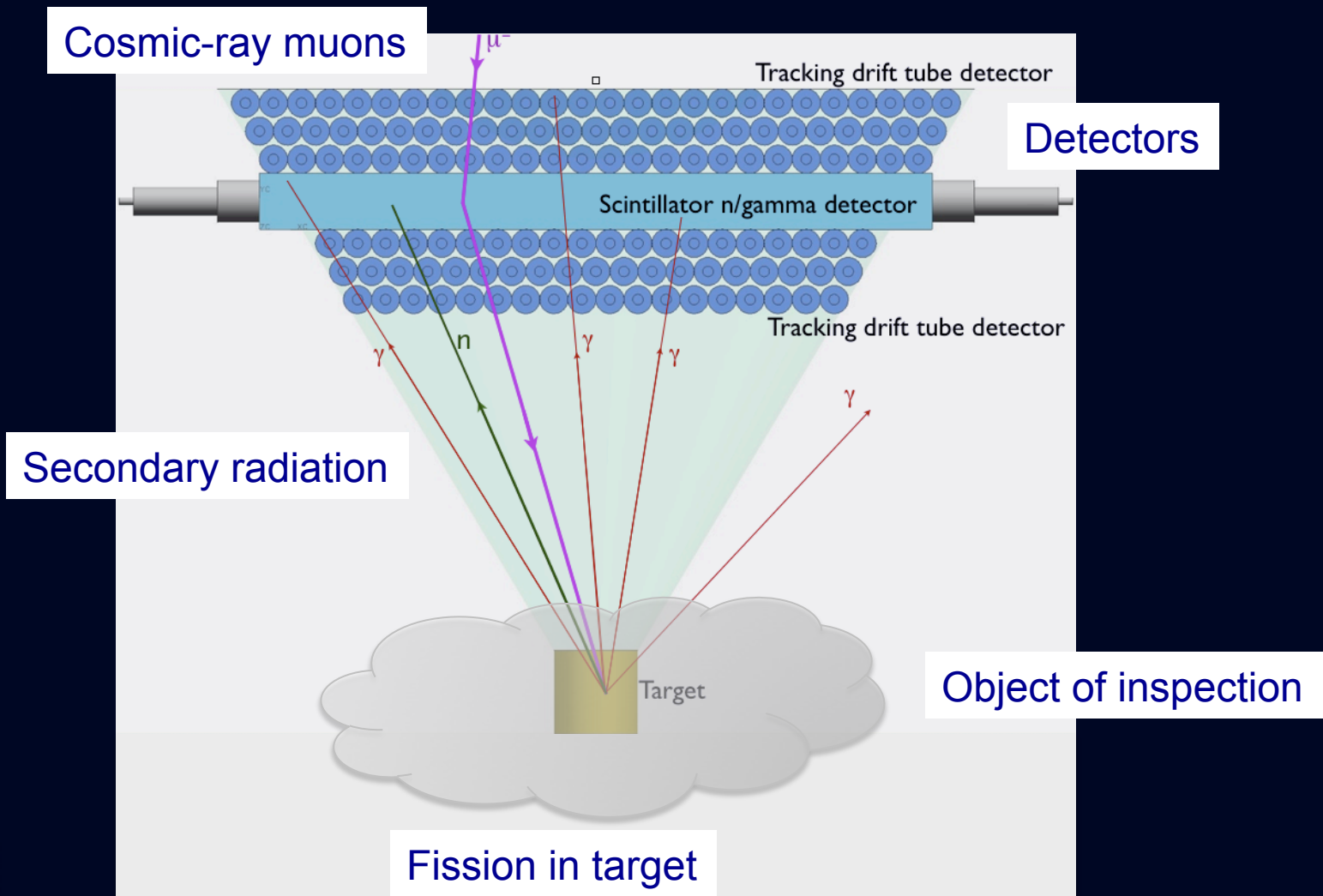
- Get an orbit and cascade down (all materials)
- Get captured by the nucleus, combine with a proton to form a neutron (increasingly high probability for higher Z)
- Nuclear in excited state, goes to main state emitting n, gammas (higher multiplicities for fissionable materials)
- Secondary fissions, chain reactions (for fissile materials)



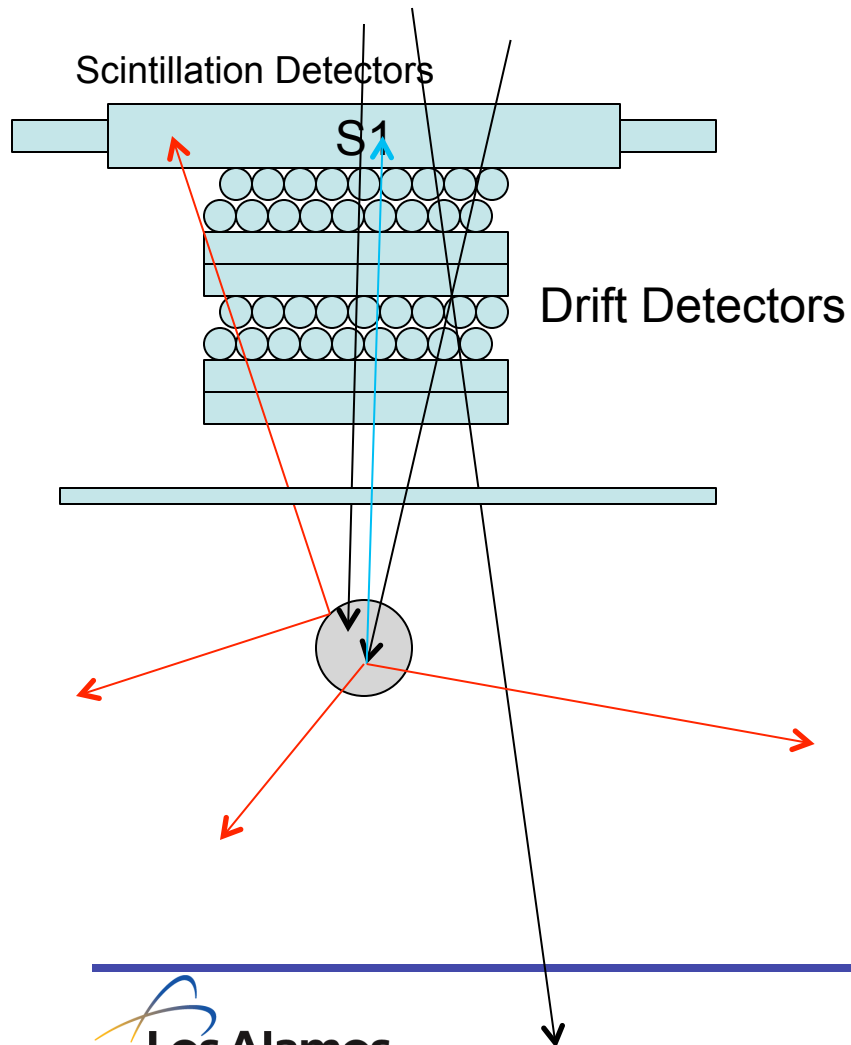
# Physics Works: Muon-Induced Fission Can Be Used to Identify SNM

- More muons stop in high-density material
- Muonic X-rays has higher energy = more penetrating for high-Z materials
- Fission is more likely, and fission products are more numerous
- Chain reaction is likely in fissile materials, not just a single event

# Muon-Induced Fission Imaging Concept



# Experimental Concept

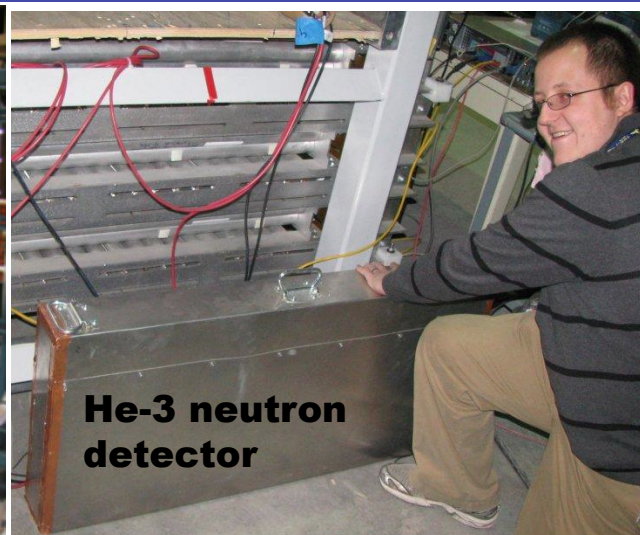


- Use charge particle tracking detectors to measure cosmic ray trajectories.
- Reconstruct dense objects with high stopping power and large secondary multiplicities using tomography.
- Measure fission radiation produced by  $\mu^-$  stopped in fissile material (Det Eff  $\sim 100\%$ ).
- Ex:  $\sim 6 \mu^-$  captured/min in 20kg U
- Coincidence counting of resulting fission gammas and neutrons  
=>  $\sim 10$  min count time

# Imaging of Cosmic Ray Muon-Induced Fission



**MMT  
muon tracker**



**He-3 neutron  
detector**



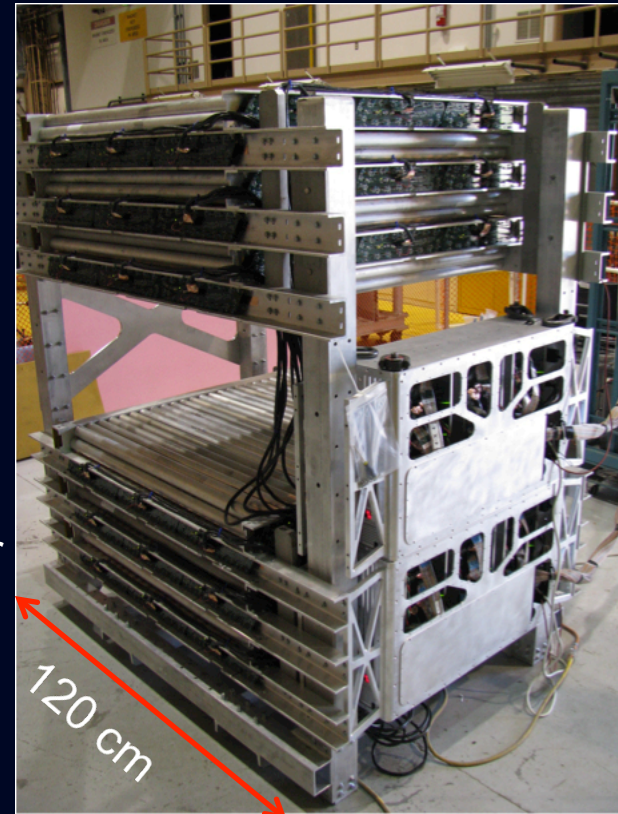
**Plastic scintillator bars (fast n/gamma detector)**

Mini-muon Tracker builds an image of cosmic-ray tracks. Coincidence with neutron counts localizes fissile material (uranium cube) in the image.

# Muon Imaging Detectors

- 576 4-foot long and 2-inch diameter aluminum drift tubes
- Each tracker set has 3 x-y pairs of double planes, for a 12-fold tracking coincidence, in and out
- Neutron detector (“suitcase”: He-3 tubes, moderator,  $\sim 0.9$  m x 0.5 m area) and gamma-detector (plastic bars with phototubes,  $\sim 1$  m long x  $10$  cm<sup>2</sup>) have been incorporated into the same data stream
- He-4 tubes and liquid scintillators are also being investigated

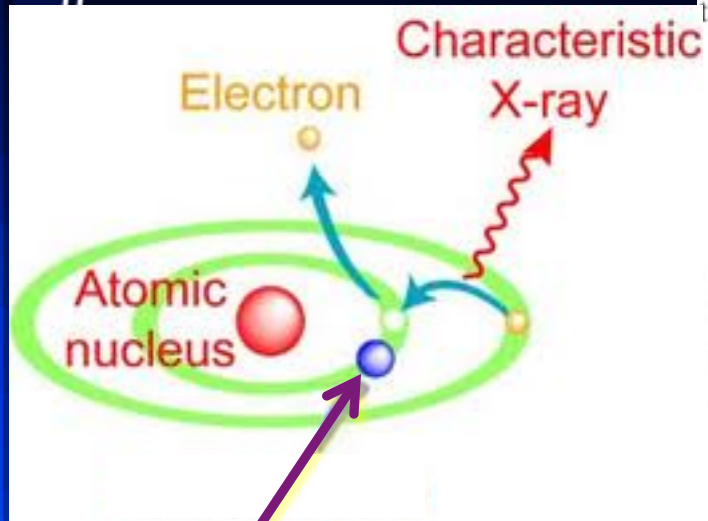
“Out”  
Tracker



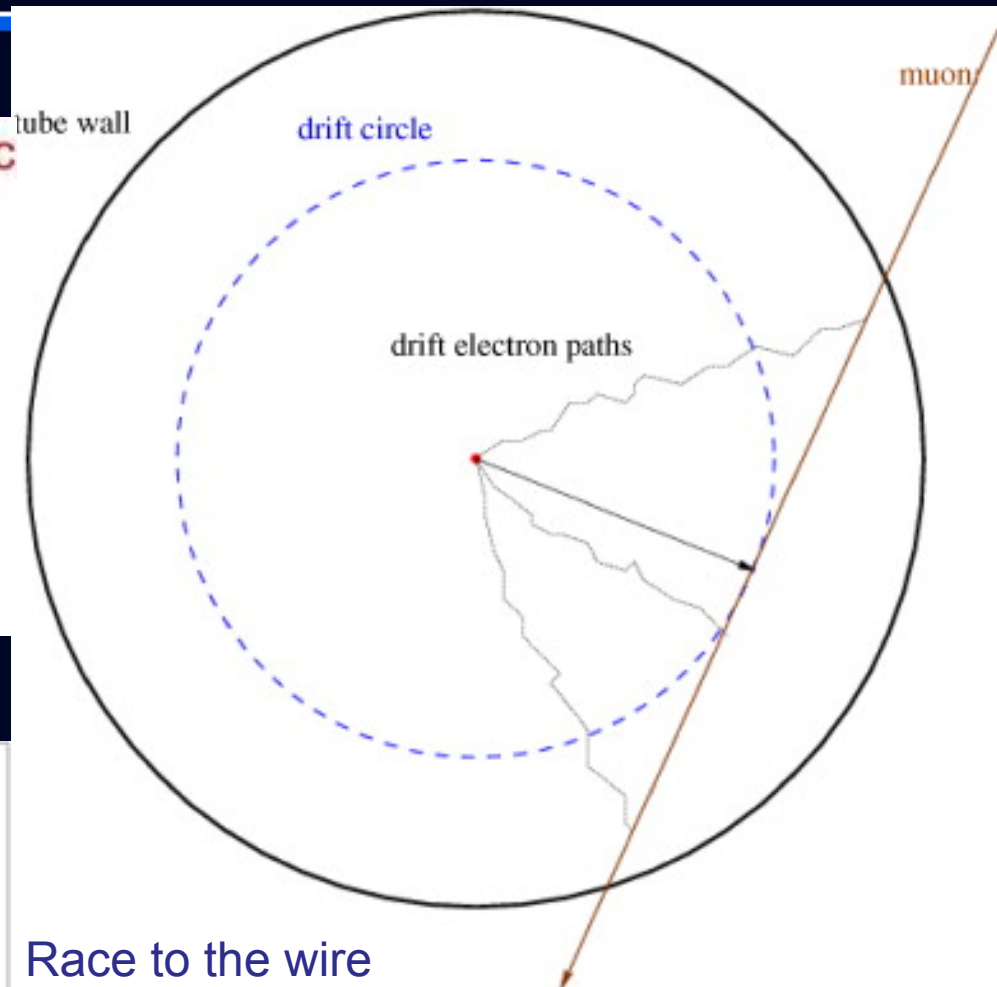
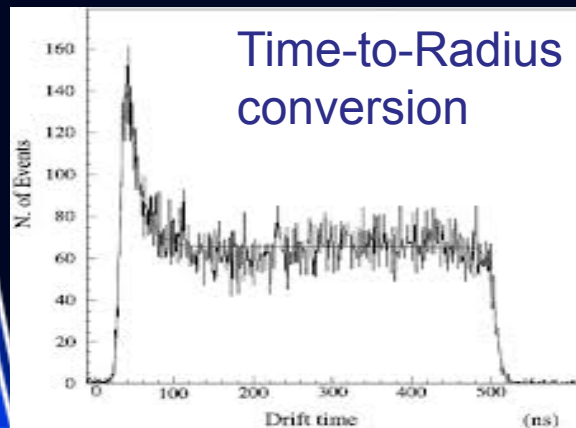
“In”  
Tracker

# Drift Tubes: **Tracking** Charged Particles

Ionization

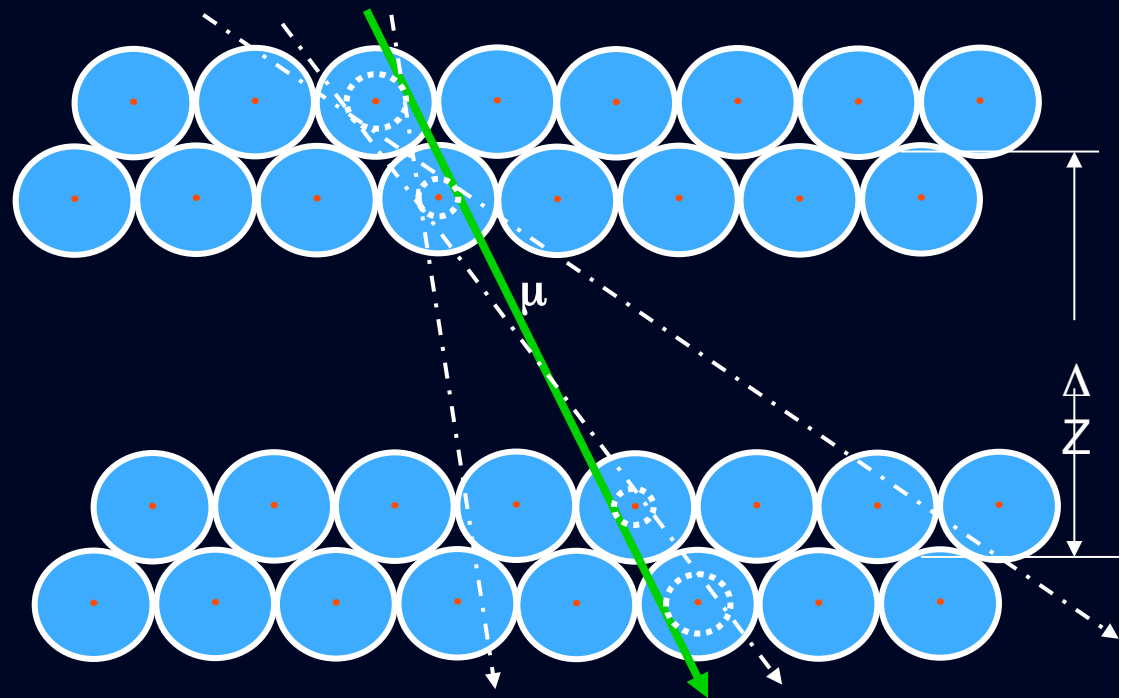


**Muon**



# Imaging is Based on Tracking Individual Muons

- Cylindrical drift tubes measure radial position of charged particles passing through
- Yields intercept and angle in two dimensions by interleaving tubes having axis oriented in x- and y- directions
- For tomography, banks of tubes are located above and below object to measure scattering angle (average scattering density)



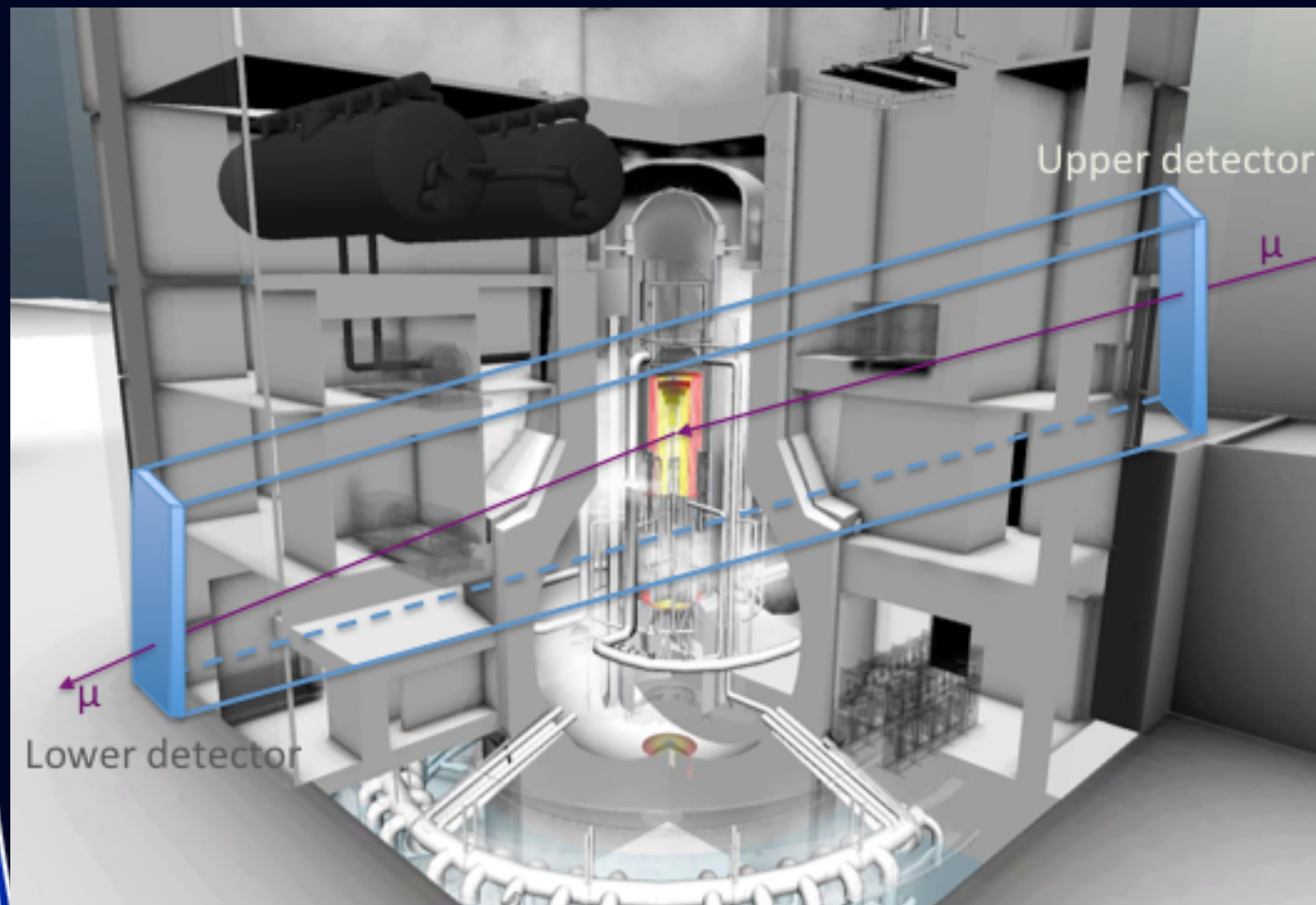
# Drift Tube Detectors Work in High-Radiation Field



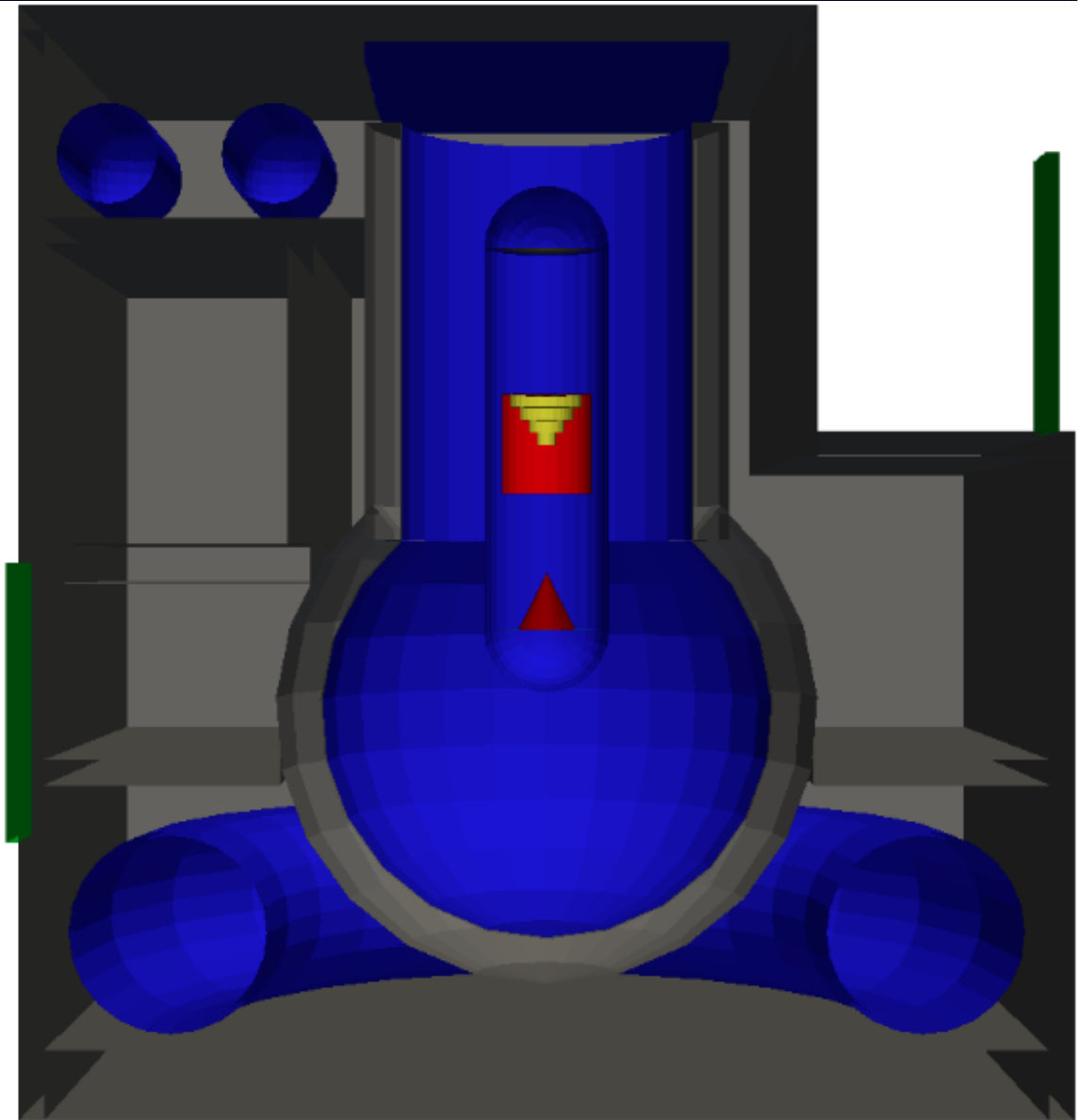
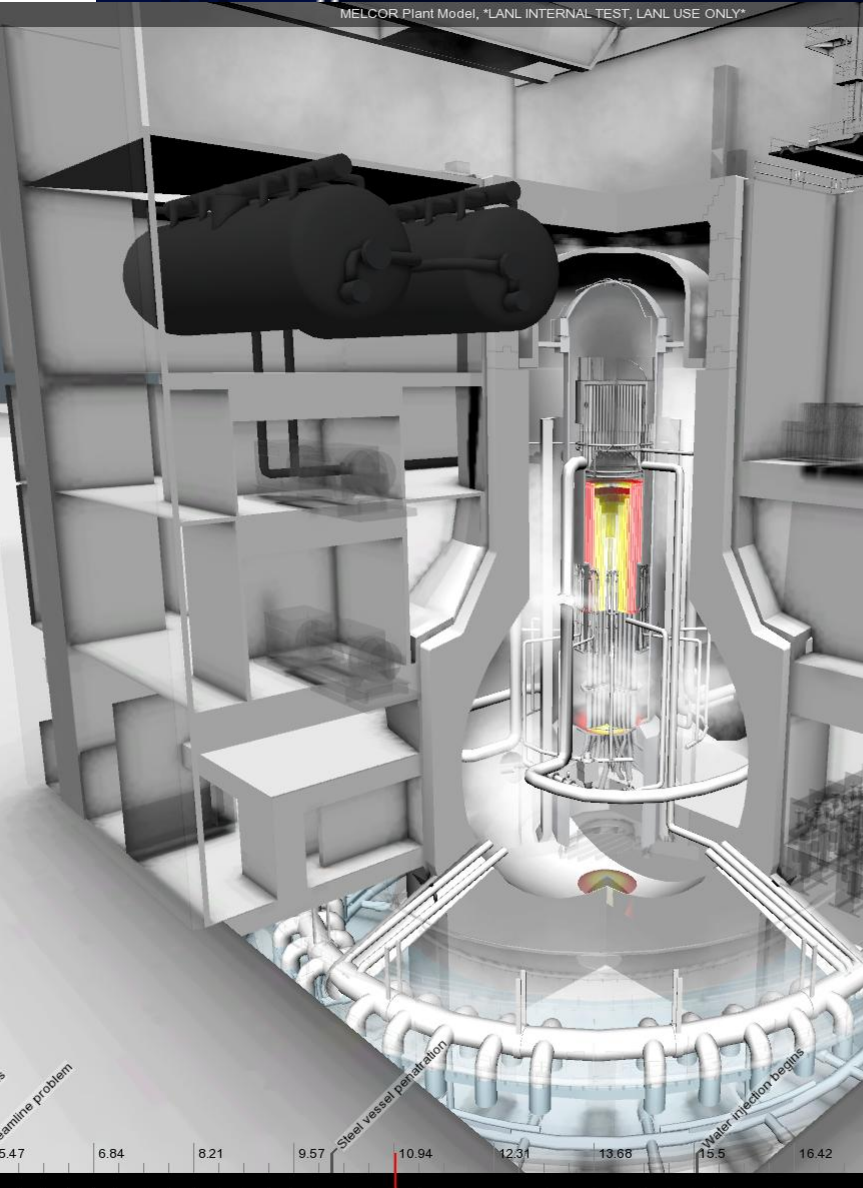
May 25, 2012 – Fukushima Daiichi Nuclear plant



# Imaging Reactor Core with Near-Horizontal Muons



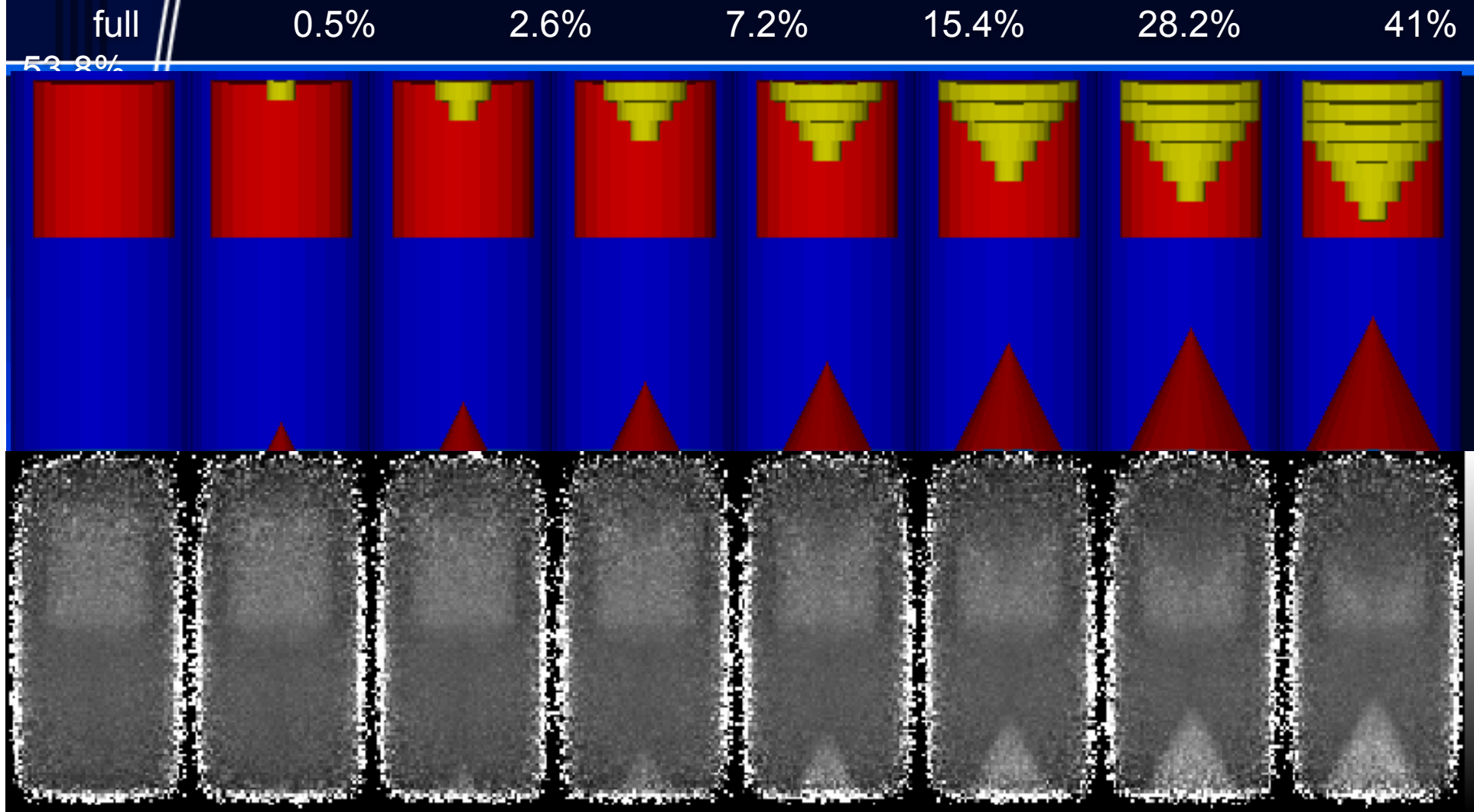
# Modeling of the Core Melting



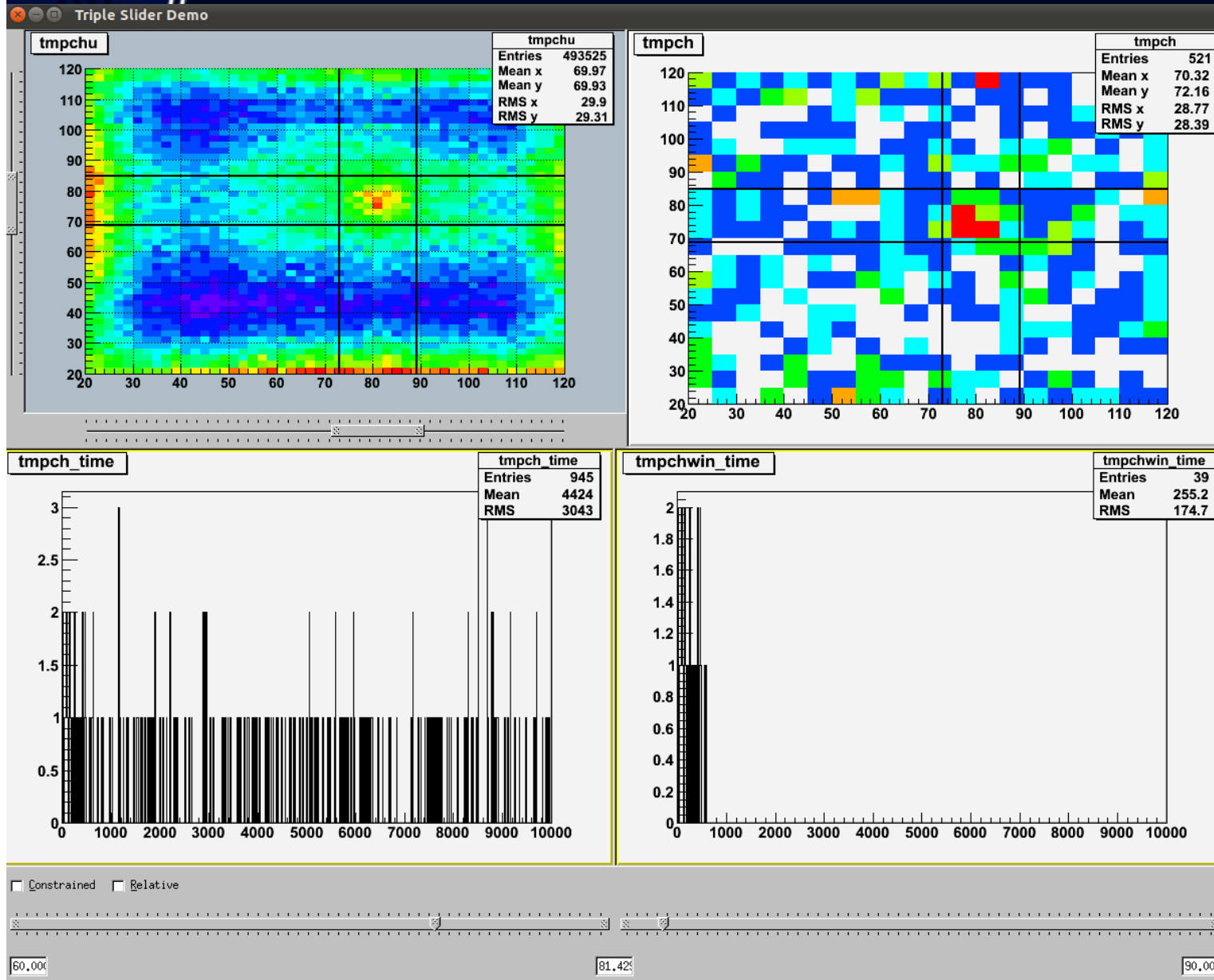
3D imaging by the VISIBLE team

Our simplified GEANT4 model

# Modeling of Melting Core



# Muon Stopping and Coincidence

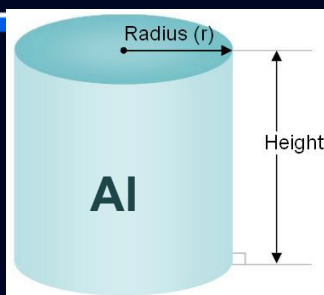


Analysis code processes raw data and creates stopped tracks and full tracks. The neutron timing is also embedded in the post-processed data stream.

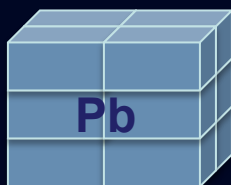
The GUI displays the results and allows the user to select regions of interest along with controlling the projection space and timing parameters for neutron coincidence.

The data shown in this GUI is of an LEU block surrounded by a doghouse of poly. The He-3 detector box was located on top of the doghouse.

# Material Identification

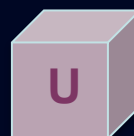


⌀16cm x 20 cm



20x10x15cm

DU ( $^{238}\text{U}$ )



10cm<sup>3</sup>

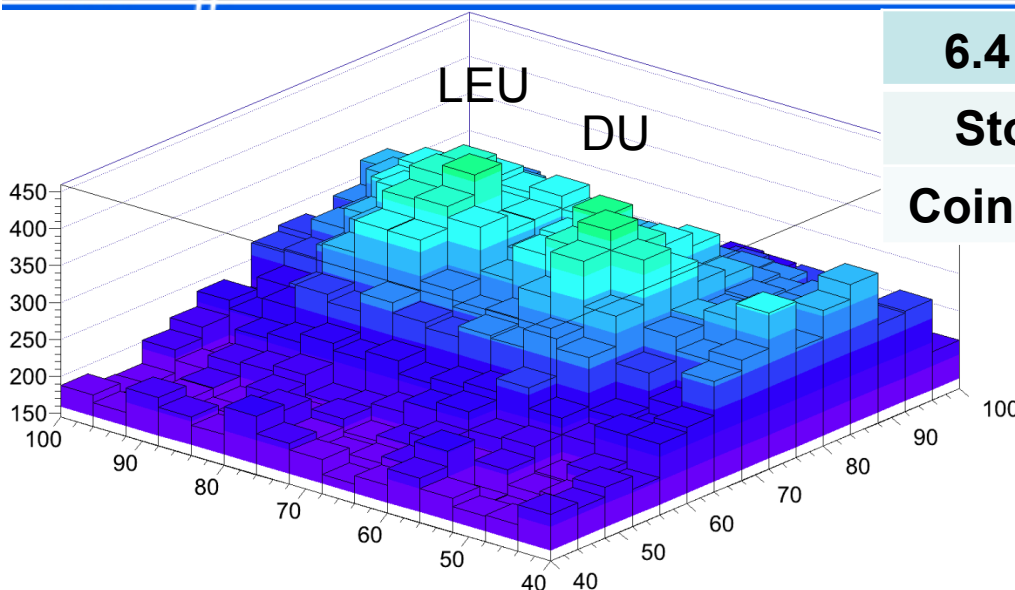
LEU (19.8%  $^{235}\text{U}$ )



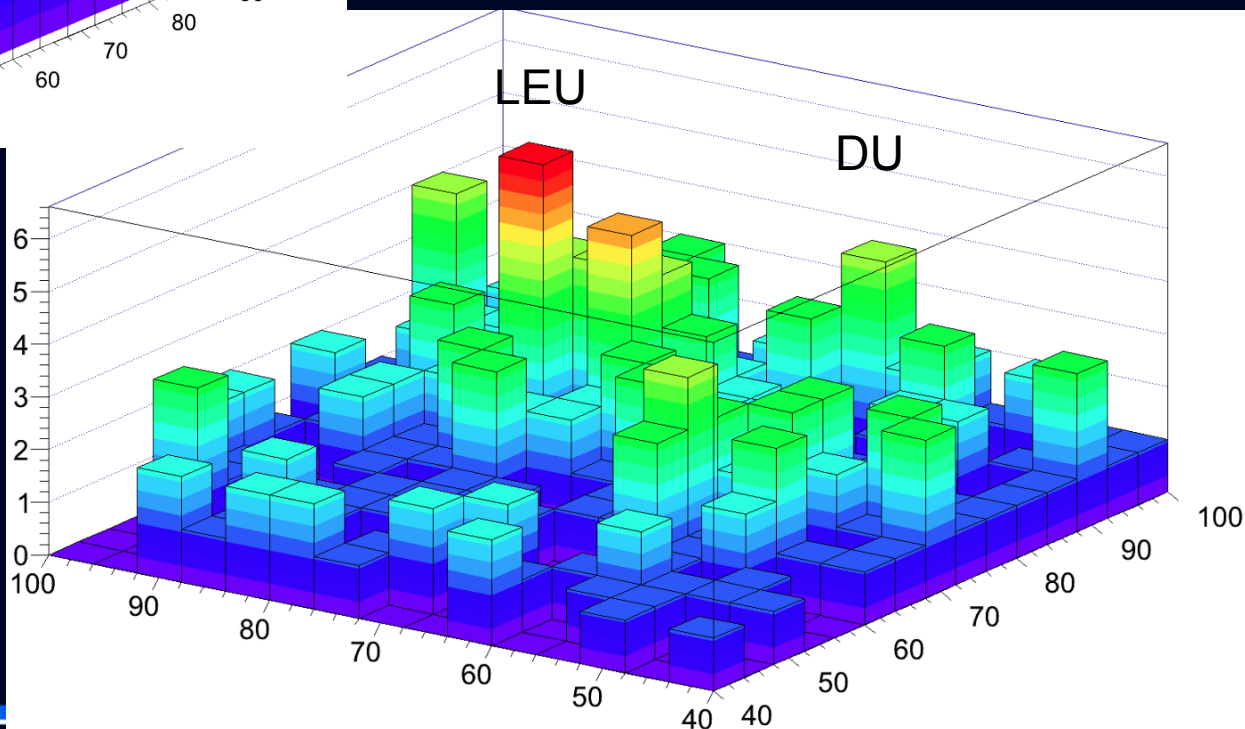
10cm<sup>3</sup>

8 hours	Al	Pb	DU	LEU	Bkg
Stopped Tracks	22191	33918	24919	26150	8688
Coinc.(plastic)	695	1303	708	989	452
Coinc.(He-3)	169	260	206	254	48
Area (sq. cm)	400	600	484	484	288
n/stopped	0.0076	0.0077	0.0083	0.0097	0.0055

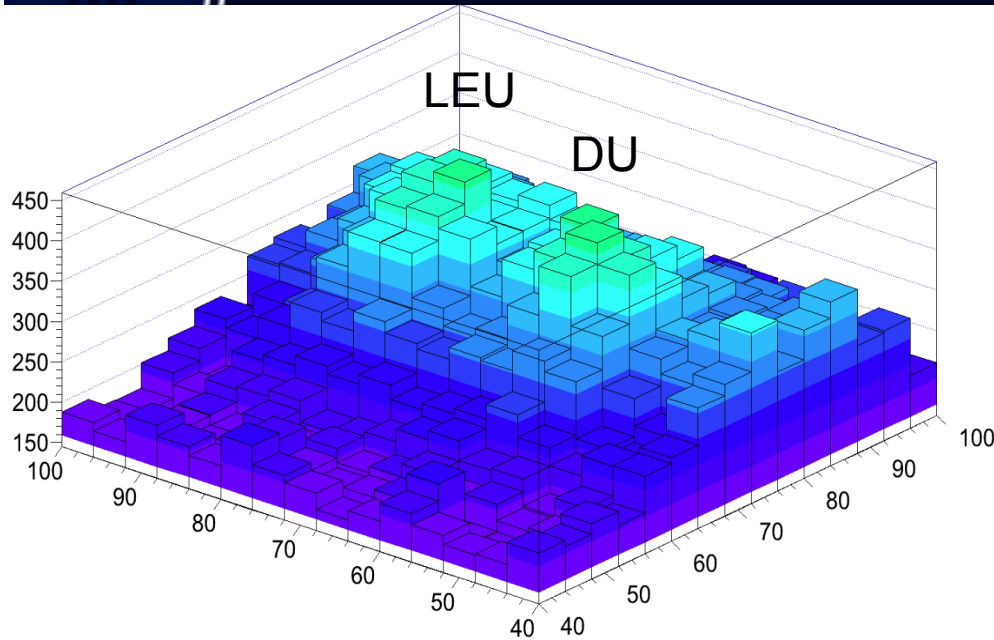
# Uranium Isotope Discrimination With He-3



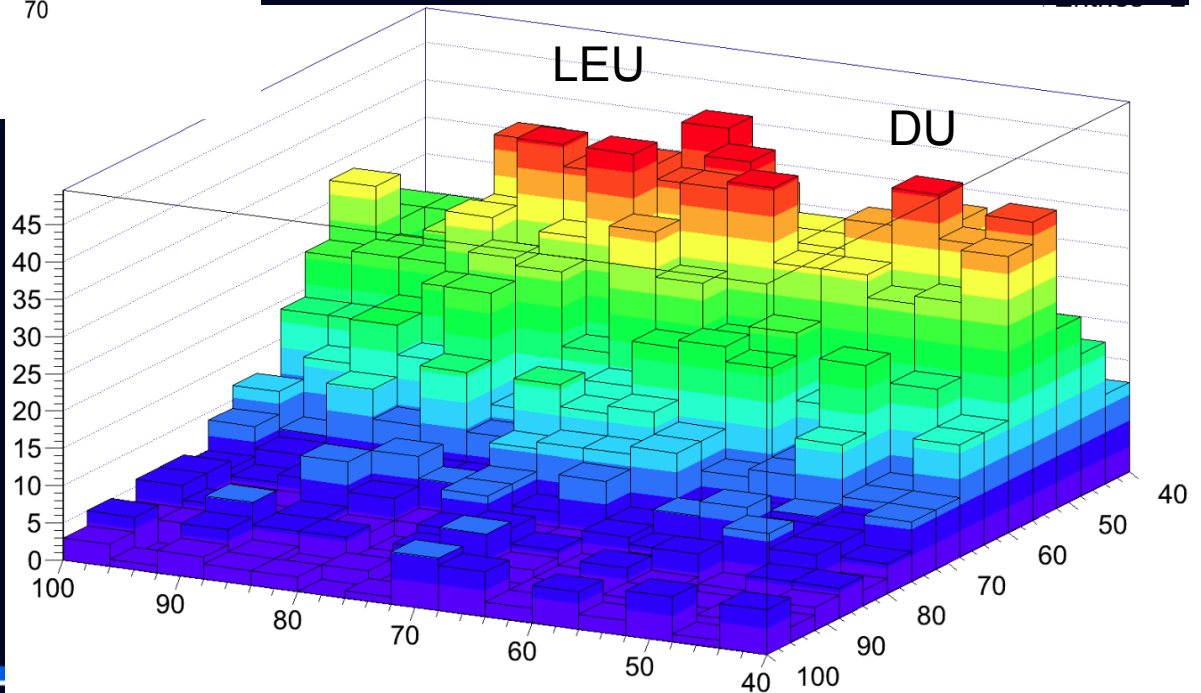
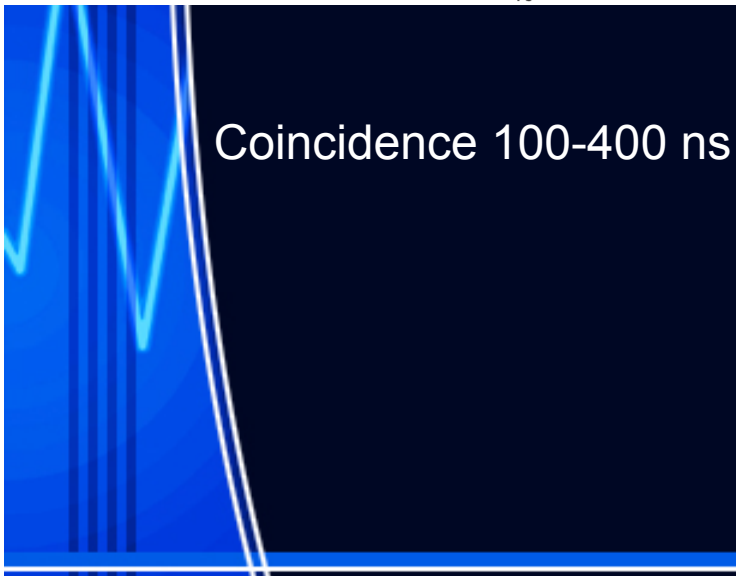
6.4 hours	LEU	DU	Bkg
Stopped	13255	13343	7599
Coincidence	77	68	29



# Uranium Isotope Discrimination with Scintillator

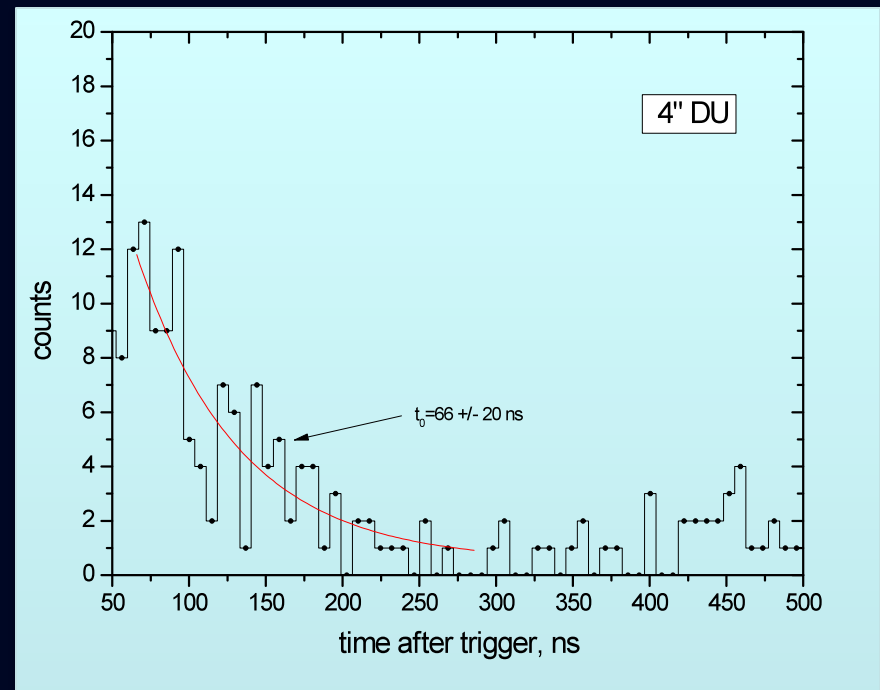


4 hours	LEU	DU	bgr
Stopped	13910	13273	13253
Coincidence	1002	854	219



# Timing Signature of Delayed Neutrons

- Fission yield per neutron stop =  $0.068 \pm 0.013$  for  $^{238}\text{U}$  and  $0.142 \pm 0.023$  for  $^{235}\text{U}$ 
  - Multiplication via k-eff further enhances  $^{235}\text{U}$  signal
  - Difficult to separate from evaporation neutrons
- Delayed component accounts for 91% of fissions in  $^{238}\text{U}$  and 88% in  $^{235}\text{U}$
- Mean lifetime =  $77.2 \pm 0.4$  ns for  $^{238}\text{U}$  and  $71.6 \pm 0.6$  ns for  $^{235}\text{U}$
- 4" x 4" DU Target @ LANL: 14 stops per minute = 1.0 fissions per minute

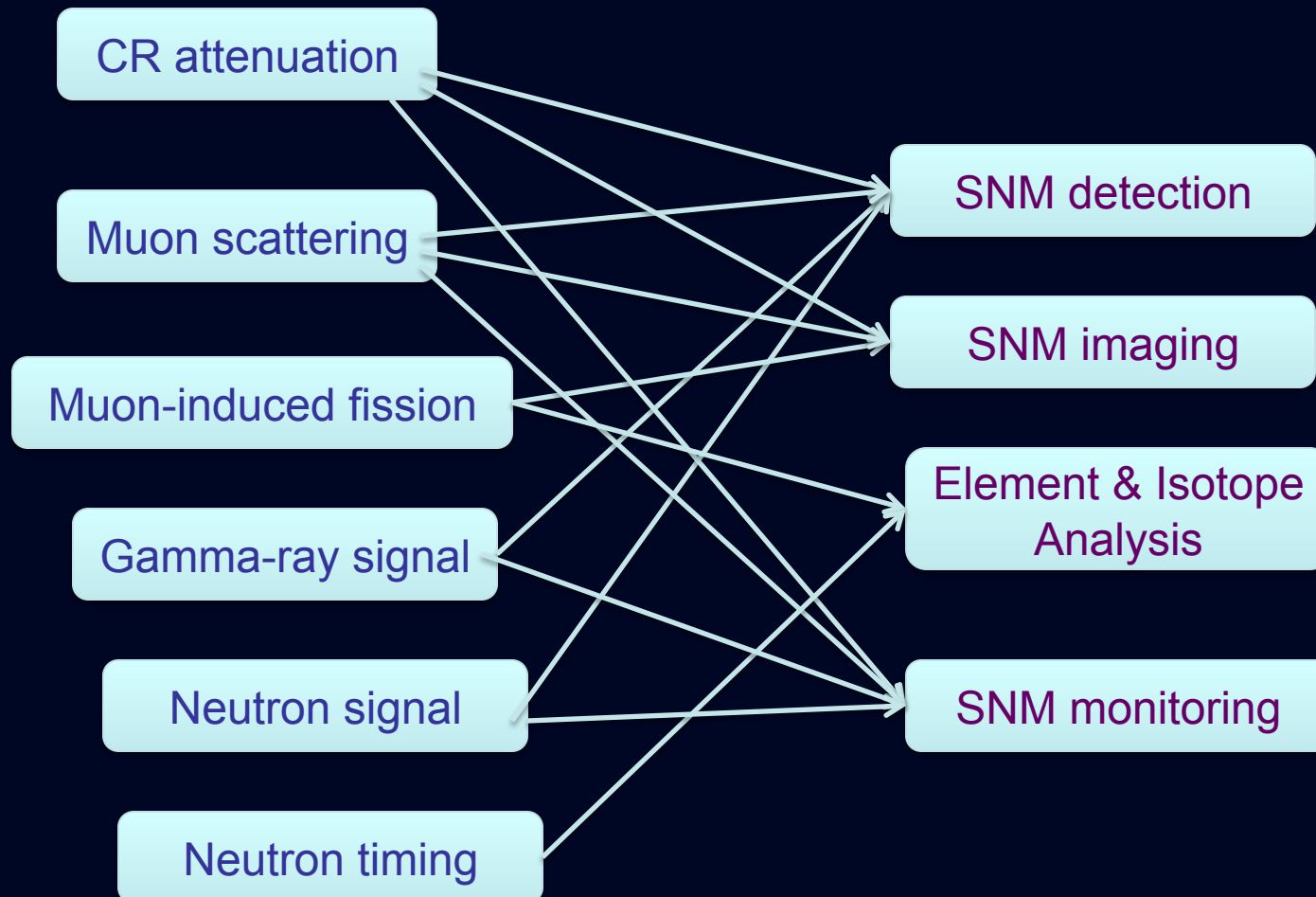


# Muon-Induced Signatures

Signature	Sensitive to	Advantages	Deficiencies
Attenuation/ absorption	<b>Amount of material/ density</b>	Simple <b>High penetration</b> Can be combined with scattering	Long exposure times Weak material separation
Scattering	Density Z-number	High-Z sensitivity 3D imaging <b>Robust scalable detectors</b>	No isotope separation Semi-static (~minutes)
Muon-induced fission	Fissionable material	Material and isotope specific	Long exposure times

# Combining the Signatures

Provided by our detectors:



# Acknowledgements

**Chris Morris, Larry Schultz, Cas Milner, John Perry, Randy Spaulding, Kiwhan Chung, Andy Fraser, Andrew Green, Nicolas Hengartner, Bill Priedhorsky, Alexei Klimenko, Leticia Cuellar, Gary Hogan, Richard Schirato, Haruo Miyadera, Zarija Lukic, Jeff Bacon, Andy Saunders, Steve Greene, Debbie Clark, Michael Brockwell, Margaret Teasdale, Jonathan Roybal, Nathan Reimus, Rick Chartrand, Jeff Wang, Pat McGaughey, Mark Makela, Gary Blanpied, Michael Sossong, John Ramsey, Mark Saltus, Kolo Wamba, David Schwellenbach, Derek Aberle, Wendi Dreesen et al.**

**LDRD program at LANL**

**DHS/DNDO  
Department of State  
DTRA**